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Parallels between astronauts and terrestrial patients - Taking physiotherapy rehabilitation "To infinity and beyond"

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PARALLELS BETWEEN ASTRONAUTS AND TERRESTRIAL PATIENTS – TAKING PHYSIOTHERAPY REHABILITATION "TO INFINITY AND BEYOND"

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ABSTRACT

Exposure to the microgravity environment induces physiological changes in the cardiovascular, musculoskeletal and sensorimotor systems in healthy astronauts. As space agencies prepare for extended duration missions, it is difficult to predict the extent of the effects that prolonged exposure to microgravity will have on astronauts. Prolonged bed rest is a model used by space agencies to simulate the effects of spaceflight on the human body, and bed rest studies have provided some insights into the effects of immobilisation and inactivity. Whilst microgravity exposure is confined to a relatively small population, on return to Earth, the physiological changes seen in astronauts parallel many changes routinely seen by physiotherapists on Earth in people with low back pain (LBP), muscle wasting diseases, exposure to prolonged bed rest, elite athletes and critically ill patients in intensive care. The medical operations team at the European Space Agency are currently involved in preparing astronauts for spaceflight, advising on exercises whilst astronauts are on the International Space Station, and reconditioning astronauts following their return. There are a number of parallels between this role and contemporary roles performed by physiotherapists working with elite athletes and muscle wasting conditions. This clinical commentary will draw parallels between changes which occur to the neuromuscular system in the absence of gravity and conditions which occur on Earth. Implications for physiotherapy management of astronauts and terrestrial patients will be discussed.

Key words: Spaceflight, microgravity, reconditioning, rehabilitation, exercise

Highlights

- Neuro-musculoskeletal changes in astronauts parallel changes in patients on Earth
- Motor control training for low back pain patients is applicable to astronauts
- Astronaut reconditioning principles may be relevant to intensive care patients.
- Benefits of exchanging physiotherapy practices between space and Earth are reciprocal

1. Introduction

Physiotherapy is inextricably linked to the effects of gravity on the human body. In the early 1900's, "gravity tests" were developed (Hislop, Avers, & Brown, 2013). In the 1940's, a system for recording muscle dysfunction in people with poliomyelitis was introduced (Hislop et al., 2013) whereby grading of muscle function was accomplished using gravity and manual resistance techniques. Manual muscle testing is still conducted today, and the principles involved underpin much of the theoretical basis of contemporary physiotherapy practice. Another area directly linked with the relationship to gravity on Earth is posture. The line of gravity normally passes through the ventral part of the L3 vertebral body (Richter & Hebgen, 2006), and biomechanical models have shown that the body is best able to withstand compressive forces when positioned in a cervical lordosis, thoracic kyphosis and lumbar lordosis (Kiefer, Shirazi-Adl, & Parnianpour, 1997). Specific muscles are required to maintain posture and the term "postural muscles" was used to describe antigravity muscles which are tonically active.

Neuromuscular plasticity refers to the ability of the nervous system to adapt and change the control and properties of skeletal muscle in response to both therapeutic input and environmental stimuli (Kidd, Lawes, & Musa, 1992). Rapid remodelling of the neuro-muscular system occurs in microgravity, with animal studies demonstrating that changes in gravitational or load related cues result in a biased recruitment away from antigravity muscles (Recktenwald et al., 1999). Healthy astronauts undergo specific physiologic changes in microgravity, which, on return to Earth, manifest as physical impairments requiring a period of rehabilitation (Payne, Williams, & Trudel, 2007). Interesting parallels can be drawn between the changes seen in the neuromuscular system induced by microgravity and those seen on Earth. Some changes due to unloading in microgravity are similar to those seen in terrestrial patient populations such as spinal cord, geriatric or deconditioned bed rest patients

(Payne et al., 2007). In addition, conditions such a low back pain (LBP) and exposure to elite sports can also have specific effects on the neuromuscular system which bear some resemblance to changes seen in astronauts. The benefits of exchanging knowledge and expertise between the two environments are therefore reciprocal.

Space agencies are currently preparing for extended duration missions, including exploration of Mars. In addition, more members of the general public may be exposed to microgravity in the future due to increased availability of commercial human spaceflight. Current long duration missions to the International Space Station (ISS) are 6 months long on average. Ultra-long duration space travel, such as interplanetary space travel to Mars, would result in 3 years or more in microgravity. Physiologic adaptation to microgravity is dependent on exposure, with greater levels of disability anticipated on returning to Earth after longer missions (Payne et al., 2007). Combining the knowledge and understanding of the effects of microgravity with the expertise of those involved in rehabilitation is therefore required.

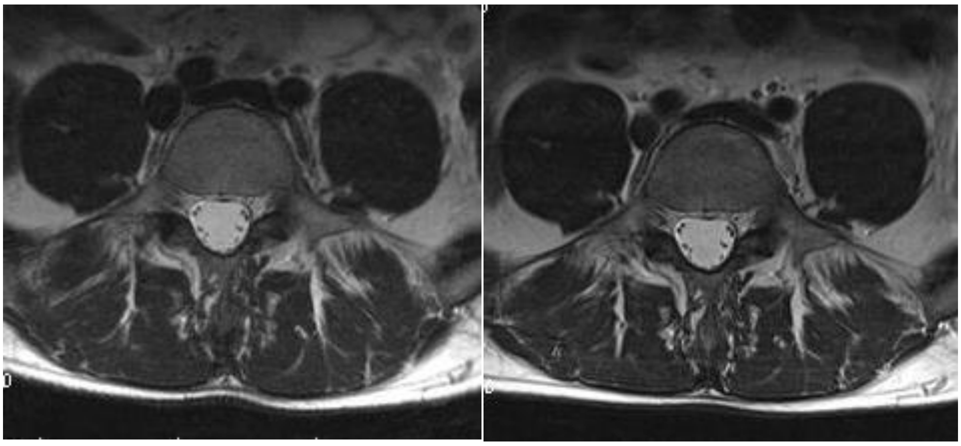
The aims of this clinical commentary are to:

1) Outline and discuss conditions on Earth and their physiotherapy management which could inform reconditioning of astronauts.
2) Draw parallels between changes which occur to the neuromuscular system in the absence of gravity in both astronauts and the terrestrial population, which could help physiotherapists better understand and prescribe interventions to the patient on Earth and the astronaut involved in spaceflight.

2. Lessons from Prolonged Bed Rest studies

Prolonged bed rest is a model used to simulate the effects of spaceflight on the human body (Nicogossian & Dietlein, 1982). Subjects follow a strict protocol of lying down in bed at a 6 degree head down tilt for days to months.

A 60 day bed rest study (2nd Berlin Bed Rest study- BBR-2) assessed lower limb muscles and showed that the response to bed rest was not uniform (Miokovic, Armbrecht, Felsenberg, & Belavy, 2012). In the lumbo-pelvic region, increases in disc volume, spinal length, loss of the lower lumbar lordosis, and changes in muscle size occur (Belavy, Armbrecht, Richardson, Felsenberg, & Hides, 2011). The rate of muscle atrophy was greatest in the multifidus muscle (L4 and L5 vertebral levels) and the lumbar erector spinae (at L1 and L2). In contrast, the size of the psoas muscle at the trunk increased (Belavy et al., 2011; Hides et al., 2007).



(a) *(b)*

Figure 1: Transverse Magnetic Resonance Image (MRI) at L4 vertebral level (a) start and (b) end of 60 days bed rest, showing atrophy of the multfidus muscles, but not of the psoas muscles. (MRIs reproduced with permission from Prof D Felsenberg and Dr D Belavy).

Bed rest studies constitute a direct link between space research and rehabilitation medicine (Payne et al., 2007). In the BBR-2, two physiotherapists were provided with a unique opportunity. The European Space Agency (ESA) physiotherapist (Lambrecht et al. 2017) and a physiotherapist experienced in motor control training designed and delivered a reconditioning program. Magnetic resonance imaging (MRI) of the lumbo-pelvic region was conducted at the start and end of bed rest and during the recovery period. After bed rest, participants underwent either trunk flexor and general strength (TFS) training or specific motor control training (MCT). MCT was based on combining the approaches used by the two physiotherapists (Hides, Lambrecht, et al., 2011). Both exercise programs restored the multifidus muscle but further increases in psoas muscle size were seen in the TFS group up to 14 days after bed rest. Results suggest that incorporation of weight bearing exercises in good spinal alignment increased the atrophied multifidus muscles, and decreased the size of the increased psoas muscles.

(a) *(b)*

Figure 2. (a) Trunk flexor and general strength (TFS) training and (b) specific motor control training (MCT) following prolonged bed rest.

3. Motor control training for astronauts and terrestrial populations

The ESA approach to post space mission lumbo-pelvic reconditioning has been published (Evetts et al., 2014; Lambrecht et al. 2017; Petersen et al. 2017). Whilst the physiotherapy programme encompassed much more than rehabilitation of the lumbo-pelvic region, a recent case history documented changes in lumbo-pelvic muscles associated with spaceflight (Hides et al. 2017). Results showed that reconditioning post spaceflight restored the sizes of the multifidus and anterolateral abdominal muscles. Data from other astronauts pre and post spaceflight are currently being collected by the ESA medical operations team.

4. Lessons from the patient with low back pain and elite athletes

A similar MCT approach has been used on Earth for people with acute LBP, chronic LBP, elite cricketers and elite Australian Football League players (Hides et al., 1996; Hides et al., 2008; Hides, Stanton, Mendis, Gildea, & Sexton, 2012). The programme has been shown to decrease LBP, was commensurate with decreased games missed due to injury and was predictive of injury (Hides & Stanton, 2016; Hides et al , 2011; Hides, Mendis, et al., 2016; Hides et al, 2014). The program also restored the size of hip muscles such as the gluteus medius, most likely due to performance of weight bearing exercises in good femoropelvic alignment (Mendis & Hides, 2016). The FIFA 11+ used as a warm-up by football (soccer) players is perhaps the most widely implemented neuromuscular exercise injury prevention programme currently used (Soligard et al. 2010). More targeted preventive training programmes are now being developed for specific sports and occupational cohorts (Padua et al., 2014).

Movement screening in the elite athlete comprises two types of tests: physical performance tests, which assess function and provide objective (quantitative) data, e.g. Triple Single Leg Hop, Star Excursion Balance Test (Hegedus et al 2014; 2015), and movement control tests, which assess quality of movement and provide qualitative observation data. Movement control tests identify and rate functional compensations, asymmetries, impairments or efficiency of movement control through transitional (e.g. single knee bend, squat, sit-stand, lunge) or dynamic (hopping, walking, landing, cutting) movements tasks. Several movement control screening tools exist, e.g. the functional movement screen or FMS (Kiesel et al., 2007) the Nine Test Screening Battery (Frohm et al., 2011) and the Performance Matrix (Mottram & Comerford 2008). However, consensus is needed to harmonise terminology and definitions used (Teyhen et al 2014; Hegedus et al 2015) and further research required for movement tests to be implemented in pre- and post- spaceflight screening.

5. Lessons from rehabilitation in intensive care

Survivors of critical illness experience significant deconditioning which can have detrimental effects on quality of life for years after recovery (Herridge et al., 2011). The well-known consequences of bed rest are compounded in critically ill patients by systemic inflammation associated with sepsis resulting in up to 12% muscle loss within the first week of illness (Puthucheary at al., 2013). Further heavy sedation and use of neuromuscular blocking drugs can induce complete ‘mechanical silence’ of the muscles. Physiotherapy for critically ill patients needs to start early to prevent deconditioning. Choice of therapy depends primarily on the patient’s level of consciousness, whether they have volitional movement and whether they are able to follow instructions. If able the patients are engaged in increasingly demanding active interventions. If patients are unable to actively participate they receive passive interventions (Gosselink et al., 2008; Sommers et al., 2015) in an effort to maintain joint range of movement and prevent muscle loss. Very early rehabilitation (within 2-5 days of critical illness) attempts to attenuate this rapid deconditioning and has focused on non-volitional mobility therapy. Studies applying unilateral continuous passive movement (daily for 9-10 hours over 7-10 days) in sedated critically ill patients can preserve muscle architecture, reduce protein loss (Griffiths et al., 1994) and help preserve force generation capacity of muscle (llano-Diez et al., 2012). The introduction of cycle ergometry into intensive care units (ICUs) means that both passive and active cycling can be implemented from the very early stages of illness (Piers-Neto et al., 2013, Burtin et al., 2009).

Figure 3: Cycle ergometry, including passive and active movements, is useful within the very early stages of critical illness (with permission).

Neuromuscular electrical stimulation (NEMS) creates passive contraction of skeletal muscle. Its use increases muscular blood flow, oxidative capabilities and maximal force generation capacity (Bax et al., 2005). Similar effects are seen in the critically ill with preserved muscle mass (Gerovasili et al., 2009), improved function and improved microcirculation (Gerovasili et al., 2009), which has been shown to have both local and systemic effects (Routsi et al., 2010). In chronically ventilated patients mobility therapy with NEMS results in significantly improved muscle strength compared to those who receive standard mobility therapy alone (Zanotti et al., 2003), although these effects have not yet been reproduced in the critically ill (Kho et al., 2015). A potential alternative to NEMS is functional electrical stimulation (FES) which differs from NEMS in that it stimulates muscles in functional patterns. FES in conjunction with cycle ergometry may be potentially beneficial to patients who are not able to partake in volitional exercise (Parry et al., 2014). Investigations as to whether this is beneficial alone or in conjunction with applied resistance are in development. Attempts to counter the chronic loss of neuromuscular function and performance in association with prolonged exposure to microgravity might benefit from considering modified use of some of the positive techniques in development in intensive care rehabilitation practice today.

6. Lessons from Rehabilitation of Muscle Wasting Diseases (Neuromuscular Diseases)

A number of the changes in the neuromusculoskeletal and sensorimotor systems seen after spaceflight or prolonged bed rest are similar to the secondary deconditioning effects seen in people with neurological disorders.

6.1 Muscle atrophy

People with neuromuscular diseases (NMDs) experience marked atrophy and weakness caused by diseases of the anterior horn cell, peripheral nerves, or muscle tissue. MRI studies exploring primary and secondary muscle atrophy in NMDs has enabled greater understanding of the mechanism of weakness and muscle function in this group. In primary muscle atrophy there is replacement with fat tissue due to muscle fibre necrosis or long term denervation (Morrow et al., 2015). Similar fatty infiltration has also been observed with aging (Hogrel et al., 2015). People with NMDs tend to be sedentary and volume loss is also observed in muscles not affected by the primary disease, with associated reduced muscle strength (Morrow et al., 2015). This is thought to be secondary, disuse atrophy and is a key focus of rehabilitation programmes in conditions where there is no reversal or treatment of the disease process (Ramdharry et al., 2010). Secondary atrophy tends to be chronic and long term, so may be a good model for comparison with microgravity induced deconditioning.

6.2 Sensory impairment

People with polyneuropathies commonly experience sensory impairment, particularly of proprioception (van der Linden et al., 2010).Transcranial magnetic stimulation suggests that NMDs with sensory impairment may have reduced central activation, implying central changes to the sensory pathways where there has been limited feedback (Schillings et al., 2007). This has implications for astronauts who may experience central changes due to altered sensory feedback. Central reinterpretation of sensory input impacts postflight gait and balance (Mulavara et al., 2010; Wood et al., 2015). Altered proprioceptive feedback can affect joint moments and power generation during gait, plus poor postural stability and increased visual dependency (Mazzaro et al., 2005; van der Linden et al., 2010.)

6.3 Fatigue and fatigability

Fatigue and fatigability have specific definitions. A common way of describing types of fatigue use the following categories: physiological (peripheral) and central fatigue

(Taylor & Gandevia, 2008) though experienced fatigue has also been described in relation to people with NMDs (Schillings et al., 2007). Fatigue in NMDs and other neurological conditions is known to be multi-factorial (Schillings et al., 2007; Kalkman et al., 2007) and may be of more concern for astronauts in long duration missions than current ISS missions.

Strategies used in people with neuromuscular diseases (NMDs), may have relevance to space rehabilitation. A relevant comparison may be rehabilitation of chronic secondary disuse and deconditioning in the less affected muscles groups/ sensory systems of people with lifelong NMDs. A number of studies have investigated both strength and cardiovascular training protocols for a spectrum of nerve and muscle diseases. For strength training, significant effects were observed with 16 to 24 week programmes using standard protocols recommended by the American College of Sports Medicine (Ramdharry et al. 2014; Lindeman et al., 1995). It is worth considering that the effect sizes to achieve functional improvement in these chronic, long term conditions may be a lot smaller than those required by astronauts to get back to pre-flight levels. An additional in-flight countermeasure that could be considered for such muscle groups is electrical stimulation. It has been explored in critical illness polyneuropathy and critical illness myopathy, and is used in the Russian space programme, however its efficacy is yet to be fully established (Hermans et al., 2014).

Rehabilitation strategies which challenge the sensorimotor control systems have also been explored in polyneuropathies. Small exploratory studies of moving and vibrating platforms show some potential in patients with neuropathy (Yoosefinejad et al., 2015) and vestibular dysfunction (Nardone et al. 2010). Vibrating insoles have also showed improvements in balance parameters in people with diabetic peripheral neuropathy (Ites et al., 2011).

Functional and exercise training have also shown benefits in patients with neuropathy, including Tai Chi showing improvements in balance (Ahn & Song, 2012), proprioceptive balance training as part of mixed programmes that include lower limb strengthening (Ites et al., 2011) and improvements in laboratory based balance measures after multi-sensory balance training (Missaoui & Thoumie, 2013). It would appear that functional training requires several weeks to demonstrate change, but some of the higher tech approaches may give faster results. The studies to date are small, however, and we must still consider the differences in effect size required for people with NMDs to show functional improvement, and the effect size required for astronauts to return to pre-flight function.

Progressive muscular atrophy in microgravity has been documented by several researchers (diPrampero & Narici 2003; Fitts et al., 2000; Akima et al., 2000; Riley, 1999, Riley, 2000; Vandenberg, 1999; Leblanc et al., 1995). Without countermeasures, muscle mass has been shown to plateau at two thirds of the initial mass after about 270 days (diPrampero & Narici 2003). Atrophy has been shown to be greatest in postural antigravity muscles (diPrampero & Narici 2003; Fitts et al., 2000; Tesch et al 2005). NMDs that are “single incident” and undergo full or partial recovery provide some parallels with deconditioning in astronauts, e.g. Guillain Barre syndrome (GBS), critical illness polyneuropathy (CIP) and critical illness myopathy (CIM). Recovery from these conditions, however, also relies on recovery from a pathological process and can take several months, so direct application to astronauts may be limited. Nevertheless, parallels with space rehabilitation may become more relevant for longer missions.

7. Conclusions

So what do elite athletes, people with LBP and other neuromuscular conditions on Earth have in common with astronauts? There are many parallels which can be drawn, and research on astronauts and terrestrial people is reciprocal and mutually beneficial. This clinical commentary has endeavoured to outline and discuss conditions on Earth and their physiotherapy management which could inform reconditioning of astronauts. In addition, drawing parallels between changes which occur to the neuromuscular system in the absence of gravity could help physiotherapists better understand interventions for the terrestrial population. Only the future can tell whether lessons learned on Earth will ultimately assist the astronauts to go to and return from "infinity and beyond"…

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